1950

The effect of pressure prehydration on the strength of hydraulic cement concrete

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THE EFFECT OF PRESSURE PREHYDRATION
ON
THE STRENGTH OF HYDRAULIC CEMENT CONCRETE

BY

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A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

Rolla, Missouri

Approved by E W Carlton
Professor of Civil Engineering

ACKNOWLEDGMENT

I wish to express my thanks to Professor E. W. Carlton of the Civil Engineering Department for his encouragement, advice, and constructive evaluation of the idea which is set forth in these papers.

I am also grateful to Mr. Orlan King, who, as head of the departmental shop, offered a number of helpful suggestions in the solution of construction problems which arose while fabricating the equipment used in these experiments.

To Dr. P.G. Herold I am indebted for the use of the Ceramics Department's mixer, which constituted a very valuable part of the apparatus used to conduct this investigation.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

HISTORICAL SKETCH AND BACKGROUND

The history of concrete is both old and new. Time has obscured the early discovery that burnt lime would provide a more lasting binder of stone than would clay. The Egyptians employed for the pyramids a gypsum binder, made by lightly burning chips of limestone. The Carthaginians, long before the Christian Era, built an aqueduct seventy miles long in northern Africa, using natural cement in the work. The Greeks were acquainted with cement, but favored for construction purposes large uncemented blocks of stone. Ruins of both Mexico and Peru show the employment of natural cement as a binding material.(1) The Romans, however, were

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(1) Hadley, Earl J., The Majic Powder, p. 7, 9.

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the master builders of concrete structures of ancient times, using it in the construction of arches, domes, roads, buildings, and aqueducts, some of which are preserved in a remarkable state of repair after the lapse of more than two thousand years.

And yet in 1909 the total of concrete roads in the United States was only six and one-half miles!(2) Thus the

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(2) Hadley, Ibid., p. 119.

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past thirty years practically covers the history of concrete as we know it today. Almost every instant of the day we are dependent directly or indirectly upon some concrete product. Concrete supports the roof over our head, lifts us from the mud, stores and carries our water and takes away waste, makes possible rapid transportation through the use of roads, bridges, tunnels, etc., protects us from fire hazards, furnishes us with recreation in the form of tennis courts and swimming pools, and performs other innumerable functions.

The original portland cement patent was granted to Joseph Aspdin, a bricklayer, in 1824.(3) This marked the

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(3) Hadley, Op. cit., p. 13.

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beginning of the gradual transition from the use of natural cement to the almost exclusive use of portland cement.

Up until the beginning of the Twentieth Century, the manufacture of portland cement concrete was by today's standards a crude process.

The discovery of the importance of the water-cement ratio by Dr. Duff A. Abrams marked the beginning of the scientific approach. The innumerable volumes written on the subject of concrete and cement attest to the vast store of knowledge of the subject accumulated since that time.

One of the most critical items in the production of concrete is the curing or hydration of the cement. During the curing process a "jel" is formed by the cement, and upon hardening, this "jel" binds together the aggregate of the mixture. This process is usually accomplished by either inundating the concrete, or by protecting its water from evaporating by other methods until a considerable portion of the ultimate strength is obtained. The curing may be accelerated to a certain extent by the inclusion of certain admixtures. The use of steam to furnish heat and to prevent evaporation will also accelerate curing.

Mr. R.J. Wig(4) performed a series of tests for the

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(4) Wig, R.J., Technologic Papers of the Bureau of Standards No. t, The Effect of High Pressure Steam on the Crushing Strength of Portland Cement Mortar and Concrete, September, 1911.

Bureau of Standards in which he cured specimens in a pressurized steam tank at pressures ranging up to eighty pounds per square inch for varying periods of time. He found that the optimum increase in strength of the treated specimens over the untreated ones was about 400 per cent after two days to 100 per cent after twenty-eight days.

Although this method has been adapted to the processing of small concrete products, its limitations in curing concrete used in structures such as buildings, bridges, and roads is evident, for no tank could accomodate such structures.

The use of calcium chloride will considerably increase the early strength of concrete, although this gain over non-treated specimens is not maintained in such a high degree after a period of several months.(5)

(5) Bulletin, Solvay Sales Division, Allied Chemical and Dye Corporation, New York, The Effects of Calcium Chloride on Portland Cement.

High early strength cement will also reduce the curing time required to give a useable strength, but it is more expensive than normal portland cement.

PURPOSE AND OBJECT OF INVESTIGATIONS

It appears that the rapidity of curing and the degree of ultimate strength of concrete can be influenced by both chemical and physical factors. The main function of the physical factors involved seems to be the creating of a more intimate combination of the cement and water, which are the active ingredients. For example, finer grinding of the cement would present more surface area to the water; the application of heat would decrease the amount of surface tension of the water, in addition to speeding the chemical reaction; steam under pressure would force water into the porous particles of cement; and the retaining of water in the mix by protecting it from evaporation would insure a more complete hydration.

It would logically follow that the application of pressure to force water into the cement particles would produce a more intimate combination of cement and water.

The purposes of this investigation are as follows:

(1) To determine if the use of pressure to force water into the cement particles will accelerate

the curing of concrete.

(2) To determine the optimum degree of pressure to be applied for a three-minute period.

(3) To determine if the accelerated curing will yield a concrete which has a higher ultimate strength after a reasonable period.

Tests of Set I are concerned with phases (1) and (2). Tests of Set II are a verification of the results of tests of Set I, under conditions of more rigid control. Tests of Set III were performed in connection with phase (3).

MATERIALS

The specimens for tests of Set I were prepared from clean common river sand, whose fineness modulus was 2.71. Its gradation is compared below with the requirements of the United States Bureau of Reclamation.

Sieve Size	Per Cent Retained (Cumulative)	Bureau of Recl. (Std. Requirements)
4	0.2	0 - 5
8	11.4	10 - 20
16	32.4	20 - 40
30	51.0	40 - 70
50	77.2	70 - 88
100	98.8	92 - 98

The cement used was normal portland cement in excellent condition manufactured by the Atlas Company. All cement used for the first set of tests came from a single sack.

The specimens for the tests of Set II were prepared from natural silica sand from Ottawa, Illinois, graded for laboratory use. The cement used was of the same type as that used for tests of Set I, and came from a single sack.

The materials used for the tests of Set III were identical with those used in the tests of Set II.

The water used in the preparation of all specimens was taken from the water system of the City of Rolla. No particular attempt was made to control the temperature, but it was noted that the average temperature was about (F) 75°, and the variation was not significant.

SPECIMENS

All specimens were two-inch mortar cubes, cast in molds conforming to specifications of A.S.T.M. Designation C 109-47.

APPARATUS

Pressure Tank: The pressure tank, shown in Fig. 1, page 7, was fabricated from an eighteen inch length of four inch diameter steel pipe, threaded on each end. On one end was placed a pipe cap, and on the other a flange. The capped end was tapped to admit a 1/2 inch pipe, to which was connected an air hose, pressure gage, and an escape valve. The flange end was equipped with a flat round plate, drilled with six 13/16 inch holes, and covered with a rubber gasket to prevent leakage. Six 3/4 inch bolts were provided to hold the flange plate in place when pressure was applied,

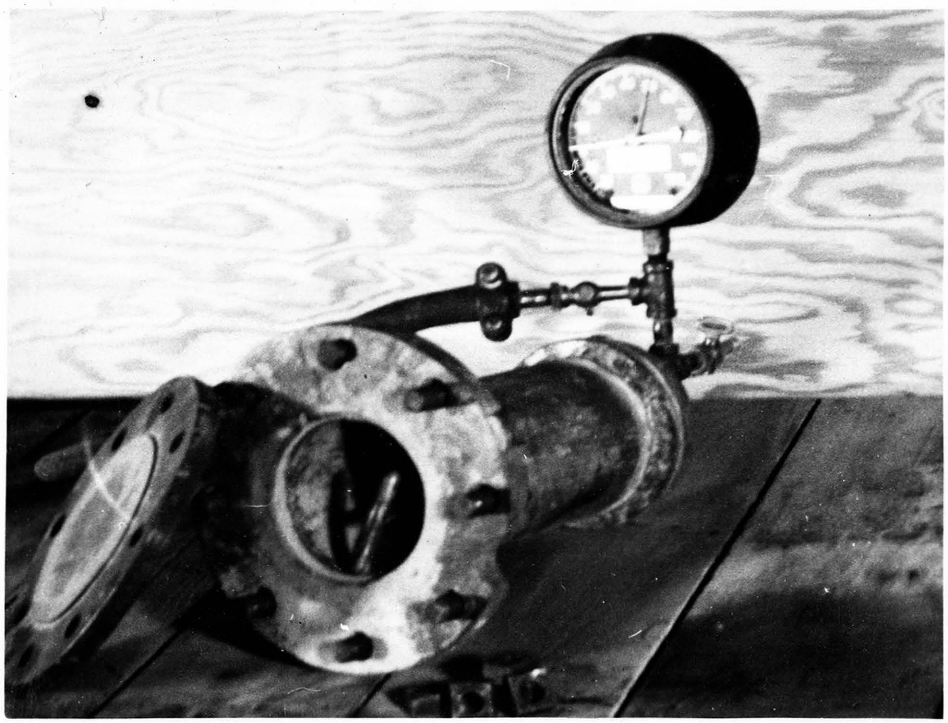


Figure 1. Pressure tank, assembled to receive batch of cement paste for pressure prehydration.

although three bolts were sufficient to prevent leakage except under the higher pressures.

In order to facilitate the complete removal of the cement paste after each application of pressure, a plunger was made to fit snugly inside the tank. It consisted of two flat circular steel plates, between which was sandwiched a circular piece of leather whose diameter was slightly greater than the inside diameter of the tank.

Considerable difficulty was experienced in making the joints between the pipe cap and the pipe and between the flange and pipe air tight. This was finally accomplished by placing a small amount of shellac in the tank, closing it, and introducing air pressure, which forced the shellac into the points of leakage. This pressure was then released; the tank was opened and the shellac allowed to dry. After repeating this operation three times the tank was leak proof, and maintained this condition throughout the tests.

Mixer: In order to eliminate in as far as possible the human equation, it was desirable to use a mechanical mixer. The small batch size eliminated the possibility of using the regular laboratory mixers. A small clay mixer, shown in Fig. 2, page 9, was obtained from the Ceramics Department, but it was found that the blade did not properly clean the sides and bottom of the mixing bowl, and therefore, did not produce a uniform mixture. This problem was overcome by removing the original blade and constructing one which would do a thorough job of mixing the mortar. The new blade was cut from two sheets of 1/4 inch brass plate, between which was placed a sheet of moderately stiff rubber. This rubber was trimmed so that its edges scraped the bottom and sides of the mixing bowl as the blade rotated and revolved. Fig. 3, page 10, illustrates the construction of the mixer blade in detail.

The motion of the mixer blade was a planetary one. The blade was eccentric with respect to the center of the stationary bowl, and revolved and rotated simultaneously. This mixer performed in an excellent manner, giving consistently uniform results.

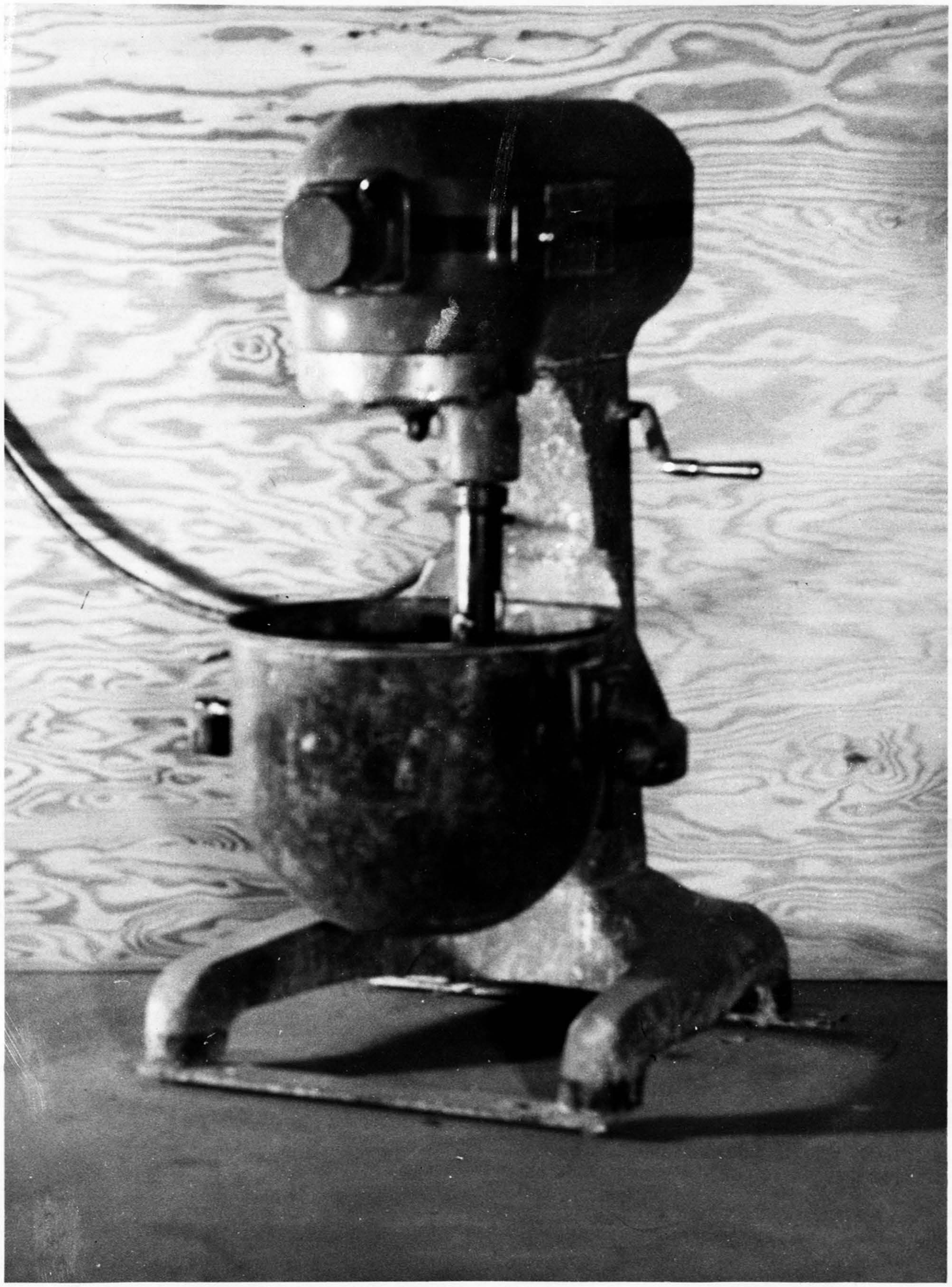


Figure 2. Mixer, with stationary bowl in position. Note eccentricity of blade stem with respect to bowl, permitting a planetary mixing motion.

Figure 3. Mixer Blade, showing details of construction. Rubber scraper around lower part of blade is clearly shown. Stem was made from a length of pipe, slotted to receive blade.

Testing Machine: For performing these tests the 200,000 pound capacity Tinius Olsen Testing Machine No. 3974, located in the Materials Testing Laboratory, Civil Engineering Department, was used. The machine was set up for a 100,000 pound limit for direct reading. The traveling head was rigged as shown in Fig. 4, below.

Figure 4. Tinius Olsen Testing Machine, with specimen in place for testing. Arrangement of traveling head may be seen, as well as lower bearing plate.

Molds: The molds used were made of machined stainless steel, conforming to A.S.T.M. Designation C 109-47. Each mold accomodated three two inch cubic specimens. The tops of the molds were not enclosed. The molds consisted of several parts, which were held in the assembled position by a single clamp. Fig. 5, below, pictures the molds, together with the smaller items of equipment.

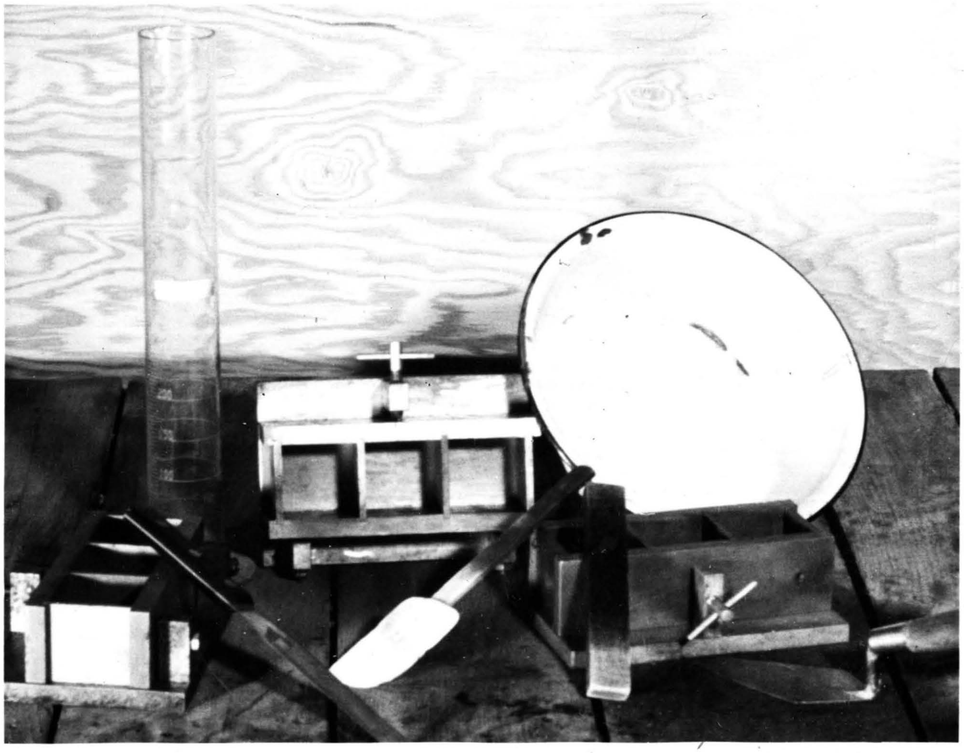


Figure 5. Smaller Items of Equipment, pictured above, required in preparing, mixing, and molding specimens. Elevation, plan, and end views of the molds are shown. A strip of adhesive tape marks the quantity of water to be used for each batch of mortar.

Smaller Items of Equipment: In addition to those pieces of apparatus mentioned, a nine inch enameled pan, a small trowel, a steel spatula, a rubber spatula, 2,000 gram capacity torsion balance with weights, a 500 cubic cemtimeter glass graduate, and a plastic tamper (cross section, 1/2 by 1 inch; length, 6 inches) were used.

TESTING PROCEDURE

Set I

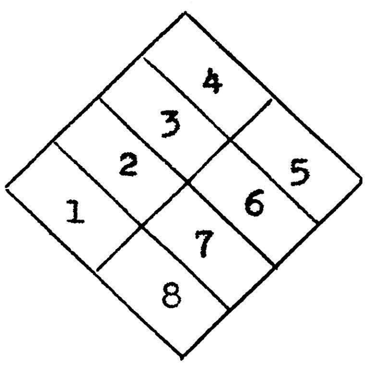
Preparation of Molds: The molds were completely disassembled and cleaned with a brass brush. The interior faces of each mold was covered with a thin film of light cup grease, and the molds were assembled. In order to prevent "bleeding" of the molds, the joints were filled from the outside with melted paraffin.

Preparation of Mortar: All equipment which came in contact with the mortar or cement paste was wet with water in order to prevent loss of water from the mix. 825 grams of cement were placed in the enameled pan, to which was added 350 cubic centimeters of water. This was thoroughly mixed, using the rubber spatula. The paste was then placed in the pressure tank, which was immediately sealed. Compressed air from the laboratory source was allowed to enter the tank until the desired pressure was obtained. This pressure was held constant for a period of three minutes, after which it was released and the tank opened.

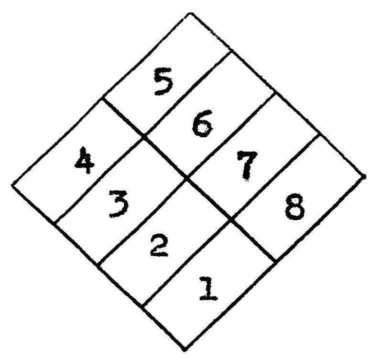
By pulling the plunger from the tank and allowing the cement paste to fall into the enameled pan, the tank was effectively cleaned.

Next the paste was placed in the mixer and agitated for 1/2 minute. At that time half of a 1650 gram batch of sand was added. After another 1/2 minute of mixing, the remainder of the sand was added and the mixer was operated for another two minutes. This gave a mixing period of sufficient length to insure complete combination of the ingredients. At the end of the mixing period the mixer was stopped, and the bowl containing the batch of mortar was removed.

Molding of Specimens: Each of the three units of the first mold was filled about one-half full of mortar. The mortar in each compartment was tamped with the plastic tamper 32 times in about ten seconds, in four rounds, each round being at right angles to the other and consisting of eight adjoining strokes over the surface of the specimen, as illustrated below:



Rounds 1 and 3



Rounds 2 and 4

After tamping the first layer in each compartment of the first mold, the compartments were filled heaping full and the tamping process repeated exactly as before.

Upon completion of the tamping, the steel spatula was used to strike off the excess mortar, and to smooth the top of each specimen. This procedure of filling the molds was repeated until all the molds were filled.

Curing the Specimens: The molds containing the specimens were placed in the moist closet for a 24 hour period. During this time they were shielded from the direct fall of water, but were otherwise exposed to the moist air.

After removal of the molds from the moist closet, the specimens were taken from the molds, tied lightly together in bundles of three, tagged for identification, and submerged in the curing tank, where a depth of water of about six inches was maintained. The specimens were cured in the tank for six days.

Testing of Specimens: When the specimens were seven days old, they were removed from the curing tank and placed in a pan of water to prevent their drying. They were taken to the testing machine and tested singly. Prior to testing, each specimen was washed thoroughly in plain water to remove loose sand particles, which might cause premature fracture of the specimen. The specimen was then placed between two small machined steel plates to provide a true bearing surface; the sides of the specimen which were in contact with the mold were placed in contact with the plates.

The upper traveling head of the testing machine was lowered until it contacted the top of the specimen and then stopped. The seating arrangement of the traveling head was carefully adjusted to prevent eccentric bearing. The balance beam of the machine was set at 300 pounds and the upper head of the machine was lowered with the machine in third gear until the beam was caused to deflect. The machine was then put in low gear and the beam was balanced.

The beam was kept balanced until the specimen ruptured. The results were read and recorded. This procedure was repeated for each specimen tested.

Set II

Preparation of Molds: Molds were prepared exactly as for Set I.

Preparation of Mortar: The same process as was used in preparing the mortar as was used in preparing that for Set I, except that 1,000 grams of cement, 330 cubic centimeters of water, and 2,000 grams of natural silica sand from Ottawa, Illinois, graded for laboratory use, were used.

Molding of Specimens: Specimens for Set II were molded exactly as those for Set I.

Curing the Specimens: Specimens for Set II were subjected to the same curing as those for Set I.

Testing of Specimens: Specimens for Set II were tested exactly as those for Set I.

Set III

The preparation, molding, curing, and testing for Set III were the same as for Set II, with the following exceptions:

Preparation: The specimens for Set III were subjected to zero or 30 pounds per square inch pressures, as indicated, rather than to the complete range of pressures, as in Set II.

Curing: The curing differed in that the specimens were left in the curing tank for the periods indicated on the accompanying graph and data sheet pertaining to Set III.

Testing: In testing specimens of Set III, specimens of each batch were alternated; that is, first a specimen of zero pressure was tested, then one of thirty pounds pressure, etc. This was done to eliminate error due to variability of conditions and handling in as much as possible.

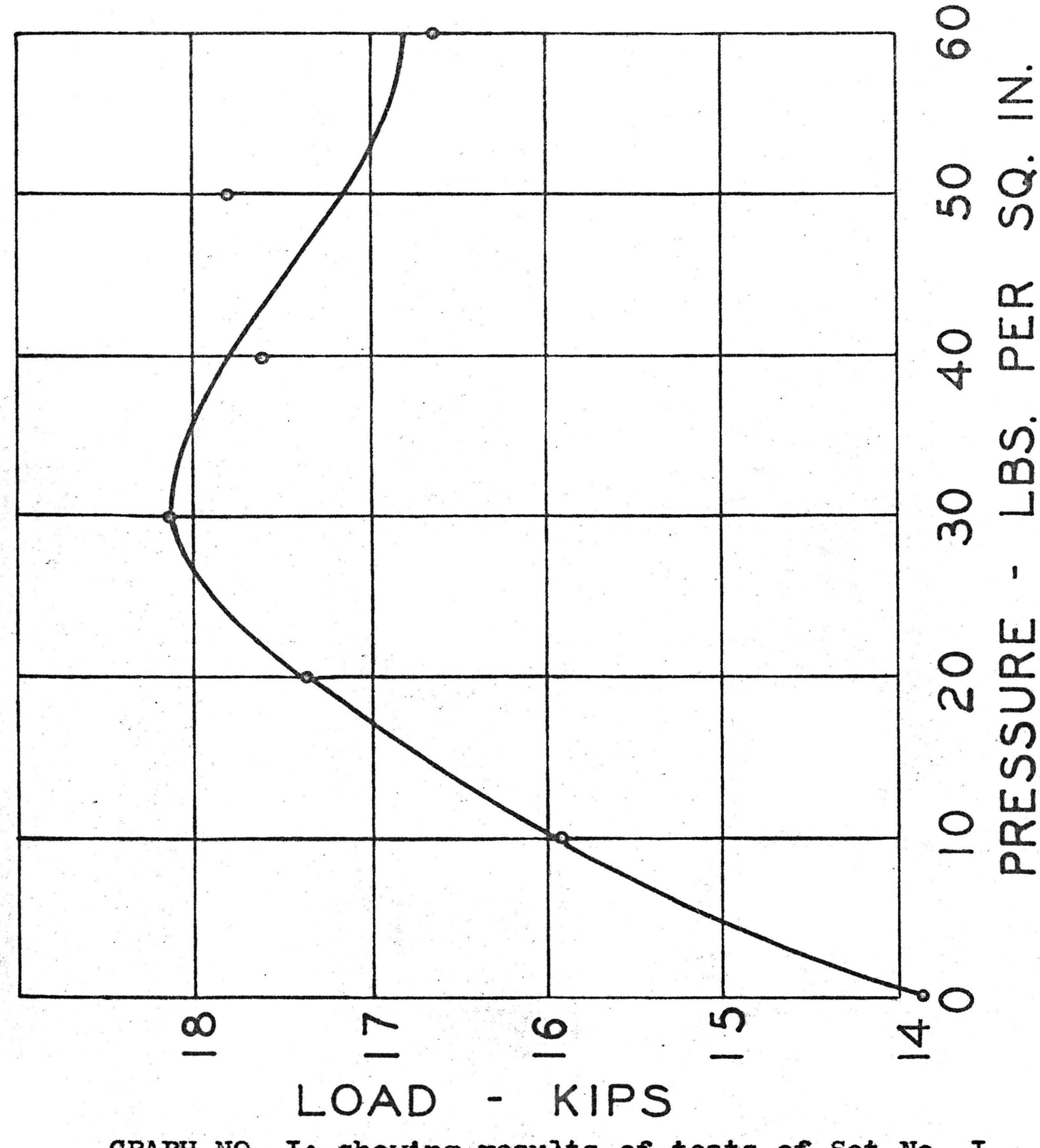
RESULTS OF TESTS OF

SET I

(Load in Pounds)

									AVG
Pressure = 0 psi									
14900	17300	14850	12200	11700	13900	11460	14300	14300	13879
Pressure = 10 psi									
16330	15340	17040	17420	16460	15580	15050	14830	15830	15987
Pressure = 20 psi									
18580	19080	18530	19110	15860	15940	16910	16210	16370	17399
Pressure = 30 psi									
18840	16730	16740	20200	19190	18030	17980	17530	18180	18158
Pressure = 40 psi									
17000	15680	18610	19420	19730	13820	17640	18580	18400	17653
Pressure = 50 psi									
12100	20900	17800	17970	16600	19340	20040	17530	18180	17829
Pressure = 60 psi									
17520	15330	17630	17700	17930	16930	15490	15840	15230	16622

Note: Specimens for Set I were two-inch cubes, made with natural sand, and aged one week.



<u>GRAPH NO. I</u>; showing results of tests of Set No. I. Each point indicates the average of nine specimens; Each specimen was a two inch cube, made with natural sand, and aged for a period of one week.

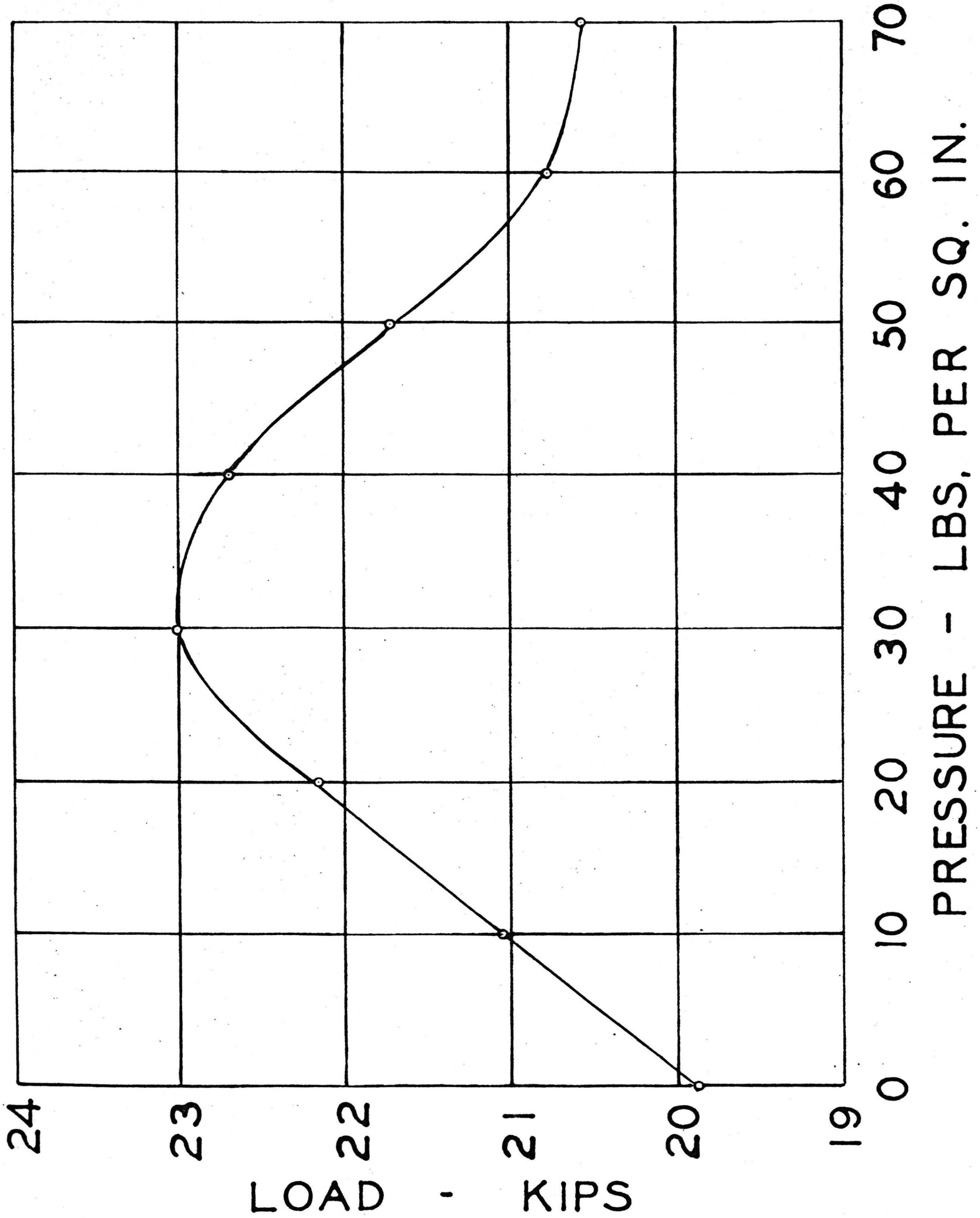
RESULTS OF TESTS OF

SET II

(Load in Pounds)

									AVG
Pressure = 0 psi									
18800	19640	18900	20000	22340	22300	19250	19330	18150	19857
Pressure = 10 psi									
19100	20780	23000	21680	19610	20850	23150	22600	19050	21090
Pressure = 20 psi									
19700	21600	24900	22000	22000	19430	22420	22790	24650	22166
Pressure = 30 psi									
23370	22260	25020	19400	25830	22230	20500	24540	23970	23017
Pressure = 40 psi									
25200	24600	21050	24540	21960	22560	21400	17230	26100	22738
Pressure = 50 psi									
21040	22170	19640	22660	22260	19340	24700	23340	20900	21783
Pressure = 60 psi									
17930	20320	18380	22260	21850	23540	20500	22100	23230	20790
Pressure = 70 psi									
18720	21200	22070	19300	21000	21650	18140	19100	24000	20576

Note: Specimens for Set II were two-inch cubes, made with Ottawa sand, and aged one week.



GRAPH NO II; showing results of tests of Set No. II. Each point indicates the average of nine specimens; Each specimen was a two inch cube, made with Ottawa sand, and aged for a period of one week.

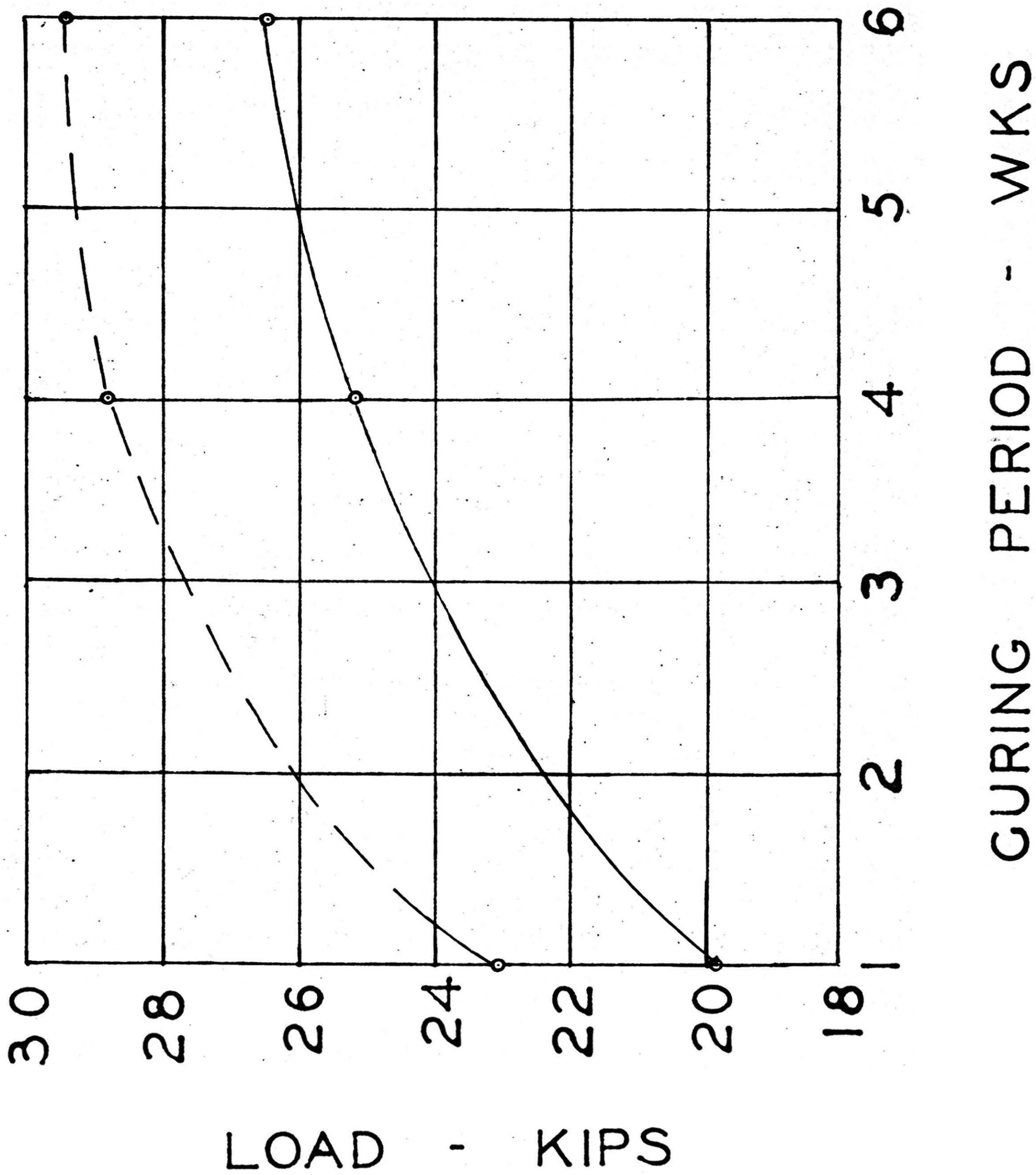
RESULTS OF TESTS OF

SET III

(Load in Pounds)

									AVG
Pressure = 0 psi; Curing Period = 1 Week									
18800	19640	18900	20000	22340	22300	19250	19330	18150	19857
Pressure = 30 psi; Curing Period = 1 Week									
23370	22260	25020	19400	25830	22230	20500	24540	23970	23017
Pressure = 0 psi; Curing Period = 4 Weeks									
23500	24430	28600	21700	26600	20420	31640	24400	25480	25197
Pressure = 30 psi; Curing Period = 4 Weeks									
25380	31240	26400	24600	31220	33550	31800	22930	31870	28777
Pressure = 0 psi; Curing Period = 6 Weeks									
24000	23570	22500	36000	26970	21460	30920	24640	24330	26043
Pressure = 30 psi; Curing Period = 6 Weeks									
26300	27780	33640	27750	33680	30200	29100	25390	30600	29381

<u>Note</u>: Specimens for Set III were two-inch cubes, made with Ottawa sand. Each batch was subjected to the pressure and curing period indicated.



GRAPH NO. III; showing results of tests of Set No. III. Each point indicates the average of nine specimens; Each specimen was a two inch cube, made with Ottawa sand, and subjected to the pressure and curing period indicated.

——————— Pressure = 0 lbs per sq in.

— — — Pressure = 30 lbs per sq in.

RESULTS

The consistent increase in strength for specimens subjected to pressure prehydration indicates that this method can be applied with considerable success. The increase in strength of 30.8 per cent for specimens made with natural sand and subjected to a pressure of thirty pounds per square inch becomes more significant when it is translated into economic terms. The savings on a large concrete structure would be noteworthy.

Since concrete is usually subjected to curing for about seven days, and since curing in the early stages is more important than that during later periods, it seems that any advantages gained before the first week would determine to a great extent the quality of the finished product.

This advantage of pressure prehydration, then, would for all practical purposes result not only in accelerated curing, but in a finished product of greater strength and durability. Tests of Set III will bear this out, for they show that the advantages of pressure prehydration are not diminished over a six week period, even though optimum curing conditions prevail.

It will be noted that the increase caused by pressure prehydration of specimens of Set II, made with Ottawa sand, is less than that of specimens of Set I. This may be explained by the fact that the limited gradation and lack of angularity in the particles of Ottawa sand are not conducive to the production of mortars with a high compressive strength, and would thus not indicate the true value of pressure prehydration.

The variability of strength for specimens within the same batch is not peculiar to this experiment, and cannot be considered, in the opinion of the writer, as a factor detracting from the value of these results. This tendency toward variability of strength was early recognized, and it was decided necessary to test a considerable number of specimens under each set of conditions investigated, in order to counteract the effect of this tendency. Nine specimens were tested in order to locate each point on the graphs included with this report, or a total of about two hundred specimens were tested, not including those many tests which were performed to determine the best procedure for carrying out this experiment.

It is of interest to note that pressures greater than about thirty pounds per square inch gave lower strengths than the thirty pounds per square inch pressure. The explanation for this may be as follows:

It may be assumed that the cement particles are to some extent porous. This allows water to enter when pressure is applied to the cement paste. The particles, however, can retain only a certain portion of this water - the surplus must bleed from the particles. For higher pressures this surplus is enough to require a considerable time to bleed out, and reach a state of equilibrium. In the interim the structure of the cement has begun to form, and the internal flowing of water partially destroys or retards this structural formation, and consequently some strength is lost.

CONCLUSIONS

The results of this experiment are highly gratifying, and exceeded even the most optimistic of the original expectations. Not only did the pressure prehydration method accelerate the curing period, but the advantages realized were maintained over such a period as to indicate their permanent retention.

The number of variable factors is so great that their investigation is necessarily beyond the scope of this thesis. It was decided to hold all variables constant within each set of tests, excepting pressure. It is believed that a shorter length of time in the pressure tank and greater pressure would give results comparable to those obtained herein. This would be of advantage in the commercial production of concrete, where the mixing time must be limited for reasons of economy.

As for the practical application of this idea to commercial production of concrete, it would be relatively simple. In the conventional types of mixers the concrete is mixed in a tank or drum. It would be a simple matter to pressurize this drum, and pressure prehydrate the cement while the ingredients are being mixed, thus making unnecessary any loss of time in the process. Some commercial mixers employ a dual phase process; that is, the ingredients are first mixed in a drum for a short period, and then are discharged into a second drum for final mixing, allowing the first drum to be recharged without loss of time. The pressure prehydration process could be very easily worked into this method without incurring loss of time.

Perhaps it would be feasible to add a small pressurized tank to the conventional mixer, and pressure prehydrate the cement paste alone, as was done in these tests.

It would be interesting to study the effect of employing a vacuum process following the pressure application. This would conceivably allow higher pressures to be used, for the surplus water could be withdrawn by means of the vacuum.

A combination of pressure and vacuum application, if alternated several times, might produce an even more thorough hydration.

While this experiment is not an end itself, it does point out promising possibilities for the advance of concrete manufacturing methods. It is believed by the author that the economies involved by the adaptation of the pressure prehydration method will be considerable, and that the results of this investigation indicate further and more complete study and research concerning this idea.

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VITA

Thomas H. Whitfield, Jr., son of Thomas H. and Mary C. Whitfield, was born in Mobile, Alabama, on May 28, 1922.

His elementary schooling was received in the Birmingham, Alabama, public school system. He graduated from high school in Demopolis, Alabama, in 1940, and attended the Massy Business College in Birmingham, Alabama, until he was employed by the Pan American Petroleum Corporation, Birmingham, Ala., in June, 1941, in the capacity of stenographer.

In December of 1941 he enlisted in the United States Army and served for a period of forty-four months, of which thirty-three months consisted of overseas duty. He was wounded in combat, returned to the United States, and was honorably discharged in August, 1945.

In September, 1945, he enrolled at the Alabama Polytechnic Institute, Auburn, Alabama, and received the degree of Bachelor of Civil Engineering in August, 1948.

He was married to Dorothy Jean Riley, daughter of Mr. and Mrs. E.D. Riley of Ashland, Alabama, in September, 1946.

Upon graduation he accepted a position on the Civil Engineering Staff at the Missouri School of Mines and Metallurgy, pursuing concurrently a course of studies leading to the degree of Master of Science in Civil Engineering.